

Some results about the Schroeder-Bernstein Property for separable Banach spaces

by

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Abstract. We construct a continuum of mutually non-isomorphic separable Banach spaces which are complemented in each other. Consequently, the Schroeder-Bernstein Index of any of these spaces is 2^{\aleph_0} . Our construction is based on a Banach space introduced by W. T. Gowers and B. Maurey in 1997. We also use classical descriptive set theory methods, as in some work of V. Ferenczi and C. Rosendal, to improve some results of P. G. Casazza and of N. J. Kalton on the Schroeder-Bernstein Property for spaces with an unconditional finite-dimensional Schauder decomposition.¹

1. Introduction

Let X and Y be Banach spaces. We write $X \overset{c}{\hookrightarrow} Y$ if X is isomorphic to a complemented subspace of Y , $X \sim Y$ if X is isomorphic to Y and $X \not\sim Y$ when X is not isomorphic to Y . We also write $X \overset{c}{\sim} Y$ if both $X \overset{c}{\hookrightarrow} Y$ and $Y \overset{c}{\hookrightarrow} X$ hold. If $n \in \mathbb{N} = \{1, 2, 3, \dots\}$, then X^n denotes the sum of n copies of X . The first infinite cardinal number will be indicated by \aleph_0 . We shall write our proofs in the case of real Banach spaces, clearly the results hold in the complex setting as well.

The Schroeder-Bernstein Problem for Banach spaces asks whether isomorphism and complemented biembeddability must coincide for any pair of Banach spaces. In other words, if X and Y are Banach spaces such that $X \overset{c}{\sim} Y$, does it follow that $X \sim Y$? It was answered by the negative by Gowers [11], using separable spaces. Later on, Gowers and Maurey [13] provided other counterexamples to the Problem: in particular, they built a separable Banach space X_1 , which is isomorphic to its cube but not to its square. So $X_1 \overset{c}{\sim} X_1^2$ while $X_1 \not\sim X_1^2$.

The answer by the negative given by Gowers to the Schroeder-Bernstein Problem opens two directions of research which are the guidelines of this paper.

1.1. The Schroeder-Bernstein Property for Banach spaces with unconditional Schauder decomposition.

The first direction of research is to ask what additional conditions ensure a positive answer to the Schroeder-Bernstein Problem. More precisely, a Banach space X is said to have the Schroeder-Bernstein Property (in short, the SBP), if whenever a Banach space Y satisfies $Y \overset{c}{\sim} X$, it follows that $Y \sim X$.

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We wish to find sufficient conditions on a Banach space to have the SBP. For example, according to the well known Pelczynski's Decomposition Method, a Banach space of the form $l_p(X)$ for $1 \leq p < +\infty$ has the SBP. For more information about Banach spaces having the SBP, see the survey of P. Casazza [2], and for more examples of Banach spaces failing the SBP, see [8].

We recall that a Banach space X is said to have a *Schauder decomposition* $X = \sum_{n \in \mathbb{N}} E_n$, where $(E_n)_{n \in \mathbb{N}}$ is a sequence of closed subspaces of X , if every $x \in X$ can be written in a unique way as $x = \sum_{n \in \mathbb{N}} x_n$, with $x_n \in E_n$ for all n . It is *unconditional* if there exists a constant C such that for all $x = \sum_{n \in \mathbb{N}} x_n$, and every subset I of \mathbb{N} , we have that $\|\sum_{n \in I} x_n\| \leq C\|x\|$. A *finite-dimensional Schauder decomposition (or FDD)* is a Schauder decomposition $X = \sum_{n \in \mathbb{N}} E_n$ for which E_n is finite-dimensional for all n . We shall use the classical abbreviation *UFDD* for an unconditional finite-dimensional Schauder decomposition.

Two important open problems about the *SBP* are to know whether every primary Banach space or every Banach space with an unconditional basis has the *SBP*. Recall that a Banach space X is said to be *primary* if whenever $X = Y \oplus Z$, then $Y \sim X$ or $Z \sim X$. The following definitions introduced by N. J. Kalton [15] are the starting point of our research in this direction.

A Banach space X has the *SBP restricted to spaces with UFDD*, if X has an UFDD and whenever a Banach space Y with UFDD satisfies $Y \lesssim X$, it follows that $Y \sim X$. A Banach space X is said to be *countably primary* if there is a countable set $(S_n)_{n \in \omega}$ of Banach spaces such that whenever $X = A \oplus B$, then there exists $n \in \omega$ such that $A \sim S_n$ or $B \sim S_n$.

Kalton obtained various results about countably primary Banach spaces with an unconditional basis or an unconditional Schauder decomposition. In particular, a countably primary Banach space with an unconditional basis has the SBP restricted to spaces with UFDD, see Theorem 2.8 in [15].

In [6], most results of Kalton concerning Banach spaces with an unconditional basis were improved. The method was simplified, using classical results of descriptive set theory. Uniformity of the constants of isomorphism was obtained. The results were also extended to κ -primary for any $\kappa < 2^\omega$ (with the obvious definition).

In Section 2, after noting that a primary Banach space with a UFDD must have the SBP (Proposition 2.1), we show how to extend the methods of [6] to the case of spaces with an unconditional Schauder decomposition. In consequence, we improve in a similar way the results of Kalton about spaces with an unconditional Schauder decomposition, and our method is also more direct. One application related to SBP is that for $\kappa < 2^\omega$, a κ -primary Banach space with an unconditional basis has the SBP restricted to spaces with UFDD (Theorem 2.10). In fact, it is more generally true of Banach spaces with an unconditional basis which are not *perfectly decomposable* (roughly speaking, a Banach space X is perfectly decomposable if there are perfectly many mutually non-isomorphic ways of decomposing X). We shall define precisely this topological notion in

Section 2.

The new uniformity result we get allows us to improve on some work of Casazza concerning primary spaces: we prove that an l_p -sum of finite-dimensional spaces, which is κ -primary for some $\kappa < 2^\omega$ (or more generally, which is not perfectly decomposable) must have the SBP (Corollary 2.12).

1.2. The Schroeder-Bernstein Index for Banach spaces.

The second direction of research about the SBP is the following. Given the existence of non trivial families of Banach spaces which are mutually non isomorphic yet complementably biembeddable in each other, we wish to know what are the possible structures for these families, for example in terms of cardinality. This question was formalized by the definition of the Schroeder-Bernstein index $SBi(X)$ of a Banach space X in [9]. Here, we shall use a modified Schroeder-Bernstein Index $SBI(X)$ given by Definition 1.1 below. This definition is simpler and more natural than the one of $SBi(X)$. Both indexes are cardinal numbers, and denoting by α^+ the successor cardinal of any cardinal α , it is direct to check that they are related by $SBi(X) = SBI(X)^+$.

Definition 1.1. Let X be a Banach space. Let $CB(X)$ be the set of subspaces Y of X such that $Y \overset{c}{\sim} X$. Let $\overline{CB}(X) = CB(X)/\sim$ be the set of isomorphism classes of elements of $CB(X)$. Then

$$SBI(X) := |\overline{CB}(X)|.$$

More simply said, $SBI(X)$ is the number of \sim -classes on the $\overset{c}{\sim}$ -class of X .

Observe that for any Banach space X , $SBI(X) = 1$ if and only if X has the SBP. Also, $SBI(X) \leq 2^{dens(X)}$, where $dens(X)$ denotes the density character of X . Indeed there is a basis of open sets for the topology of X , of cardinality $dens(X)$. So there are no more than $2^{dens(X)}$ open subsets of X , and in particular no more than $2^{dens(X)}$ (isomorphism classes of) closed subspaces of X .

Our goal is to see what are the possible values of the Schroeder-Bernstein Index for a Banach space.

Clearly the counterexample X_G of Gowers in [11] satisfies $SBI(X_G) > 1$. In 1997, Gowers and Maurey ([13], page 559) constructed, for each $p \in \mathbb{N}$, $p \geq 2$, a Banach space $X_1(\mathcal{S}_p)$ (this notation will be explicated in Section 4), which is isomorphic to its subspaces of codimension n if and only if p divides n . Consequently $SBI(X_1(\mathcal{S}_p)) \geq p$, consider the family of spaces $(X_1(\mathcal{S}_p) \oplus \mathbb{R}^n)_{0 \leq n \leq p-1}$. In fact, using the properties of $X_1(\mathcal{S}_p)$ mentioned in the remark in [13] after Theorem 19, it is not difficult to prove that $SBI(X_1(\mathcal{S}_p)) = p$.

Recently the second author [9] found a Banach space X_E such that X_E^2 is isomorphic to a complemented subspace of X_E , but X_E^m is not isomorphic to X_E^n , for every $m \neq n$. Hence $(X_E^n)_{n \in \mathbb{N}}$ is an infinite sequence of mutually non-isomorphic Banach spaces which are complemented in each other. Thus $SBI(X_E) \geq \aleph_0$.

The main aim of Section 3, and the main result of this paper, is to provide a family of cardinality the continuum of mutually non-isomorphic separable Banach spaces which are complemented in each other (Theorem 3.9). In particular, if X is any member of this family then $SBI(X) = 2^{\aleph_0}$. The construction of such a family is inspired by the construction by Gowers and Maurey of the Banach space X_1 isomorphic to its cube but not to its square ([13], Section 4.4).

In Section 4, we note some open problems about the SBP as well as some side consequences of some of our techniques. For example, we show that failing the SBP is not a three-space property (Proposition 4.3).

Finally, we end with an appendix which contains the proof of two technical lemmas needed in Section 3.

2. On the SBP restricted to Banach spaces with unconditional finite-dimensional Schauder decomposition.

We start by noting a direct and interesting consequence of Kalton's results.

Proposition 2.1. *Let X be a primary Banach space with a UFDD. Then X has the SBP.*

Proof. Being primary, X must be isomorphic to its hyperplanes. By Theorem 2.3 from [15], for some $N \in \mathbb{N}$, $X \sim X \oplus \sum_{n \geq N} E_n$, where the E_n 's are the summands of the UFDD of X . From this and from the fact that each E_n is finite-dimensional, we deduce that X must be isomorphic to its square.

But a primary space isomorphic to its square is easily seen to have the SBP. Indeed, assume $Y \overset{\sim}{\rightarrow} X$. There exists Z such that $Y \sim X \oplus Z$, so $Y \sim X \oplus Z \sim X \oplus X \oplus Z \sim X \oplus Y$. On the other hand Y embeds complementably in X , so by the primarity of X , either $Y \sim X$, and we are done, or $X \sim X \oplus Y \sim Y$.

■

We now turn to our generalization of Kalton's result about the SBP restricted to spaces with UFDD, for countably primary Banach spaces. We shall use classical results and definitions from descriptive set theory, and our reference for these will be the book of Kechris [16].

Let X be a separable Banach space with a Schauder decomposition $\sum_{n=1}^{+\infty} E_n$. We start as in [15] or [6] by assigning to each element α of 2^ω a subspace $X(\alpha)$ of X in the obvious way:

$$X(\alpha) = \sum_{\alpha(n)=1} E_n.$$

The relation of isomorphism between spaces of the form $X(\alpha)$, $\alpha \in 2^\omega$, induces a relation on 2^ω that we shall denote by \simeq , and it is not difficult to check that it is analytic.

We first give some definitions. For a cardinal $\kappa \leq 2^\omega$, we say that a Schauder decomposition is κ -primary if there is a set \mathcal{S} of Banach spaces, of cardinality κ ,

such that for every subset I of \mathbb{N} , there exists $S \in \mathcal{S}$ such that $\sum_{n \in I} E_n \sim S$ or $\sum_{n \in \mathbb{N} \setminus I} E_n \sim S$. A Banach space X is κ -primary if there is a set \mathcal{S} of Banach spaces, of cardinality κ , such that whenever $X \sim A \oplus B$, there exists $S \in \mathcal{S}$ such that $A \sim S$ or $B \sim S$. Evidently an unconditional Schauder decomposition of a κ -primary Banach space is κ -primary.

We shall say that a Schauder decomposition is *perfect* if there is a perfect subset P of 2^ω such that, for all $\alpha, \beta \in P$ with $\alpha \neq \beta$,

$$\begin{aligned} \sum_{\alpha(n)=1} E_n &\not\sim \sum_{\beta(n)=1} E_n, \\ \sum_{\alpha(n)=0} E_n &\not\sim \sum_{\beta(n)=1} E_n, \\ \sum_{\alpha(n)=0} E_n &\not\sim \sum_{\beta(n)=0} E_n. \end{aligned}$$

In particular, note that a Schauder decomposition which is κ -primary for some $\kappa < 2^\omega$, is not perfect.

For our last definition, we need to recall that the set of separable Banach spaces, seen as subspaces of an isometrically universal separable Banach space such as $C([0, 1])$, or more generally, the set of subspaces of a given separable Banach space X , may be equipped naturally with a Borel structure called the Effros-Borel structure (see e.g. [6]). In this setting we may talk about Borel or analytic sets of separable Banach spaces, or of subspaces of a given separable Banach space X ; note that any uncountable Borel set of Banach spaces is necessarily of cardinality 2^ω .

For a Banach space X , we call *decomposition* of X a pair (A_0, A_1) of subspaces of X such that $X = A_0 \oplus A_1$. We say that a separable Banach space X is *perfectly decomposable* if there is a Borel set $\{(A_\alpha^0, A_\alpha^1), \alpha \in 2^\omega\}$ of decompositions of X , such that for $\alpha \neq \beta$ and any (ϵ, γ) in $\{0, 1\}^2$, $A_\alpha^\epsilon \not\sim A_\beta^\gamma$. So a Banach space which is κ -primary for some $\kappa < 2^\omega$, is not perfectly decomposable.

Finally and evidently, if a separable Banach space has a perfect unconditional Schauder decomposition then it is perfectly decomposable.

We need to recall two theorems from descriptive set theory (Theorems 19.1 and 8.41 from [16]).

Theorem 2.2 (Kuratowski-Mycielski) *Let E be a perfect Polish space, and R be a relation on E which is meager in E^2 . Then there exists a homeomorphic copy C of the Cantor space such that $\forall x, y \in C$ with $x \neq y$, we have $x \neg R y$.*

Theorem 2.3 (Kuratowski-Ulam) *Let E be a Polish space and D be a subset of E^2 having the Baire property. Then D is nonmeager if and only if*

$$\exists^* x \exists^* y : (x, y) \in D.$$

Here $\exists^* xP(x)$ signifies the existence of a nonmeager set of x such that $P(x)$.

We are now ready to prove a proposition in the spirit of [6].

Proposition 2.4. *Let X be a separable Banach space with a Schauder decomposition $X = \sum_{n=1}^{+\infty} E_n$ which is not perfect. Then there exists an \simeq -class which is non-meager in 2^ω .*

Proof. For $\alpha \in 2^\omega$, we shall denote by $\mathcal{C}\alpha$ the element $(1 - \alpha(n))_{n \in \omega}$ of 2^ω . As in [6] we define the relations \simeq_1 and \simeq_2 on 2^ω by

$$\alpha \simeq_1 \beta \Leftrightarrow \alpha \simeq \mathcal{C}\beta,$$

$$\alpha \simeq_2 \beta \Leftrightarrow \mathcal{C}\alpha \simeq \mathcal{C}\beta.$$

The first case in our proof is to assume that \simeq , \simeq_1 and \simeq_2 are meager. Then their union is meager as well. We then apply Theorem 2.2. to get a perfect set P avoiding this union, i.e. with the property stated in the definition of perfect Schauder decompositions.

In the second case, assume for example that \simeq_2 is non-meager. Being analytic, \simeq_2 has the Baire property, so by Theorem 2.3., we may find an element $\alpha \in 2^\omega$ such that, for β in a non-meager subset of 2^ω , $\mathcal{C}\alpha \simeq \mathcal{C}\beta$. As clearly, the map sending β to $\mathcal{C}\beta$ is an homeomorphism on 2^ω , we deduce that the \simeq -class of $\mathcal{C}\alpha$ is non-meager. A similar proof holds if \simeq or \simeq_1 is non-meager. ■

Remark 2.5. In [6], it was shown that in the case of Banach space with a 1-dimensional Schauder decomposition (i.e. with a Schauder basis), a non-meager \simeq class in 2^ω must be comeager. This used the fact that modifying a finite number of vectors of the basis of a Banach space preserves the isomorphism class. We cannot use this fact in the general case of a Schauder decomposition, and in fact the result is false in that case: consider $X = l_1 \oplus (\sum l_2)_{l_2}$. We see that the \simeq -class corresponding to l_2 is non-meager but not comeager.

We now deduce from Proposition 2.4 the following extension of Theorem 3.4 from [15]. For X and Y Banach spaces, and $K \geq 1$, $X \sim^K Y$ means that X is K -isomorphic to Y .

Theorem 2.6. *Let X be a separable Banach space with an unconditional Schauder decomposition $X = \sum_{n=1}^{+\infty} E_n$ which is not perfect. Then, there exists an integer N and a constant K such that, for every subset I of $[N, \infty)$, $X \sim^K X \oplus (\sum_{n \in I} E_n)$.*

Proof. By Proposition 2.4, we assume there is a non-meager \simeq -class and we intend to find K and N such that for every subset I of $[N, \infty)$, $X \sim^K X \oplus \sum_{n \in I} E_n$. Let $X(\alpha_0)$ for some α_0 be a Banach space in the isomorphism

class associated to the non-meager \simeq -class. For $n \in \mathbb{N}$, let \mathcal{A}_n be the set of α 's such that $X(\alpha) \sim^n X(\alpha_0)$. Then for some $K \in \mathbb{N}$, $\mathcal{A} = \mathcal{A}_K$ is non-meager.

The set \mathcal{A} is analytic, thus has the Baire property, and we deduce that \mathcal{A} is comeager in some basic open set $N(u)$. Here $u = (u(1), \dots, u(k))$ denotes an element of $2^{<\omega}$. In other words the set \mathcal{C} of $\alpha \in 2^\omega$ such that the concatenation $u^\frown \alpha \in \mathcal{A}$ is comeager in 2^ω . We now apply the following classical characterization of comeager subsets of 2^ω which was already used (and proved) in [6]. As \mathcal{C} is comeager in 2^ω , then there exists a partition of \mathbb{N} in infinite subsets M_1 and M_2 , subsets $N_1 \subset M_1$ and $N_2 \subset M_2$, such that: for $i = 1, 2$, an element α of 2^ω is in \mathcal{C} whenever for every $n \in M_i$, $\alpha(n) = 1$ if $n \in N_i$ and $\alpha(n) = 0$ if $n \notin N_i$.

Going back to \mathcal{A} , we get a partition of $[k+1, +\infty)$ in infinite subsets A_1 and A_2 , subsets $B_1 \subset A_1$ and $B_2 \subset A_2$, such that: for $i = 1, 2$, an element α of 2^ω is in \mathcal{A} whenever

- (a) for every $n = 1, \dots, k$, $\alpha(i) = u(i)$, and
- (b) for every $n \in A_i$, $\alpha(n) = 1$ if $n \in B_i$ and $\alpha(n) = 0$ if $n \notin B_i$.

Now let $N = k+1$, let I be any subset of $[N, \infty)$, and let $Y = \sum_{i \in I} E_i$.

We let $C_1 = A_1 \cap I$, $C_2 = A_2 \cap I$. The element α_1 defined by $\alpha_1(i) = u(i)$, for $i < N$, and $\alpha_1(i) = 1$ if and only if $i \in C_1 \cup B_2$, for $i \geq N$, satisfies (a) and (b), so belongs to \mathcal{A} . Denoting by $X(u)$ the finite sum $\sum_{u(i)=1} E_i$, we deduce that

$$X(\alpha_0) \sim X(u) \oplus \left(\sum_{i \in C_1 \cup B_2} E_i \right).$$

By unconditionality of the basis,

$$X(\alpha_0) \sim X(u) \oplus \left(\sum_{i \in B_2} E_i \right) \oplus \left(\sum_{i \in C_1} E_i \right).$$

By the characterization of \mathcal{A} again,

$$X(\alpha_0) \sim X(\alpha_0) \oplus \left(\sum_{i \in C_1} E_i \right).$$

Likewise

$$X(\alpha_0) \sim X(\alpha_0) \oplus \left(\sum_{i \in C_2} E_i \right).$$

Combining the two, and noting that C_1, C_2 form a partition of I , we get

$$X(\alpha_0) \sim X(\alpha_0) \oplus Y.$$

As $X(\alpha_0)$ is complemented in X , we deduce

$$X \sim X \oplus Y.$$

Finally, a look at the proof shows that we can get this isomorphism with an uniform constant depending on K and the constant of unconditionality of the Schauder decomposition. ■

Concerning Theorem 2.6, note that a stronger conclusion of the form $X \sim X^2$ (as in the case of a space with an unconditional basis) is false: consider a decomposition $X = X_0 \oplus (\sum l_2)_{l_2}$, where X_0 is the hereditarily indecomposable Banach

space of Gowers and Maurey [12]. There are only four classes of isomorphism of subspaces $X(\alpha)$ (including the classes of $\{0\}$ and X_0), but it is not difficult to show that X is not isomorphic to its square.

However, as an immediate consequence of Theorem 2.6, we have:

Corollary 2.7. *Suppose that the separable Banach space X has Schauder unconditional decomposition which is not perfect, and assume also that every summand is isomorphic to its square. Then X is isomorphic to its square.*

The next theorem is a variation of Theorem 2.6. We recall that E_0 is the equivalence relation defined on 2^ω by $\alpha E_0 \beta$ if and only if $\exists m : \forall n \geq m, \alpha(n) = \beta(n)$. It is the \leq_B -lowest Borel equivalence relation above equality on 2^ω . For the definition of \leq_B : given an equivalence relation R on a Polish space E , (resp. R' on E'), we say that (E, R) is Borel reducible to (E', R') , and write $(E, R) \leq_B (E', R')$, if there is a Borel map $f : E \rightarrow E'$, such that for all x, y in E , xRy if and only if $f(x)R'f(y)$. We refer to [7] for more about the notion of the relation \leq_B of Borel reducibility between equivalence relations. When a relation reduces E_0 , in particular there is a perfect set of mutually non-related points.

In [7], a Banach space X was defined to be *ergodic* if the relation E_0 is Borel reducible to isomorphism between subspaces of X . It was proved by Ferenczi and Rosendal ([6],[18]) that a Banach space X with an unconditional basis which is not ergodic, must be isomorphic to its square, to its hyperplanes and more generally to $X \oplus Y$ for any subspace Y generated by a finite or infinite subsequence of the basis.

We can prove a result in the same spirit for Banach spaces with a UFDD, provided we (unessentially) relax the ergodic assumption. We recall that Banach spaces X and Y are *nearly isomorphic*, and write $X \xrightarrow{f} Y$, if some finite-codimensional subspace of X is isomorphic to a finite-codimensional subspace of Y . We shall say that a Banach space is *nearly ergodic* if E_0 is Borel reducible to \xrightarrow{f} between subspaces of X . The next proposition shows that when a Banach space is ergodic, then it is nearly ergodic. Note that both imply that there is a perfect set of mutually non (nearly) isomorphic subspaces.

Proposition 2.8. *Let X be an ergodic Banach space. Then it is nearly ergodic.*

Proof. By definition there exists a Borel map g from 2^ω into the set of subspaces of X , such that $\alpha E_0 \beta$ if and only if $g(\alpha) \sim^f g(\beta)$. Denote by E_f the relation defined on 2^ω by $\alpha E_f \beta$ if and only if $g(\alpha) \overset{\sim}{\sim} g(\beta)$. An E_f -class is a countable union of E_0 -classes and thus is meager. As every E_f -class is meager, then by Theorem 2.3, E_f is meager in $(2^\omega)^2$. Every E_f -class is also invariant by E_0 , so by Proposition 14 of [18], the relation E_0 is Borel reducible to E_f . Combining the map reducing E_0 to E_f with g , we get a Borel reduction of E_0

to \mathcal{L} on the set of subspaces of X . ■

Theorem 2.9. *Let X be a separable Banach space with an unconditional Schauder decomposition $X = \sum_{n=1}^{+\infty} E_n$ such that E_n is of finite dimension for $n > N$, for some N . Assume X is not nearly ergodic. Then there exists an integer k and a constant K such that, for every subset I of $[k, \infty)$, $X \sim^K X \oplus (\sum_{n \in I} E_n)$.*

Proof. Let $\overset{f}{\simeq}$ be the relation induced on 2^ω by near isomorphism between spaces of the form $X(\alpha)$, $\alpha \in 2^\omega$.

First assume $\overset{f}{\simeq}$ is meager. Let 1_N be the length N sequence $(1, \dots, 1)$. Then the relation r , defined on 2^ω by

$$\alpha r \beta \Leftrightarrow 1_N^\wedge \alpha \overset{f}{\simeq} 1_N^\wedge \beta,$$

is also meager in $(2^\omega)^2$. Furthermore, because E_n is of finite dimension for $n > N$, r is clearly invariant by a finite change of coordinates of the sequences α and β . According to Proposition 14 of [18], we deduce that E_0 is Borel reducible (by some g) to r . The map f from 2^ω into 2^ω , defined by $f(\alpha) = 1_N^\wedge g(\alpha)$, is then a Borel reduction of E_0 to $\overset{f}{\simeq}$, that is, X is nearly ergodic, a contradiction.

So assume $\overset{f}{\simeq}$ is non meager. Using Theorem 2.3 as before, we deduce that some $\overset{f}{\simeq}$ class is non-meager. This class is a countable union of \simeq -classes, so we deduce that some \simeq class is non-meager. We may then proceed as in Theorem 2.6. ■

The result of Kalton about the SBP restricted to spaces with UFDD, for countably primary Banach spaces, mentioned in the introduction, now generalizes to Banach spaces which are either not perfectly decomposable or not nearly ergodic.

Theorem 2.10. *Let X be a Banach space with an unconditional basis. Assume X is not perfectly decomposable or not nearly ergodic. Then X has the SBP restricted to spaces with UFDD.*

Proof. By Theorem 2.6 or Theorem 2.9, there exists $N \in \mathbb{N}$ such that for every $I \subset [N, +\infty)$, $X \sim X \oplus \sum_{i \in I} \mathbb{R} e_i$. Taking $I = \{N\}$ we see that X is isomorphic to its hyperplanes. Taking $I = [N, +\infty)$ it follows that X is isomorphic to its square.

Now let Y be a Banach space with an UFDD $(E_n)_{n \in \mathbb{N}}$ such that $Y \overset{\mathcal{L}}{\sim} X$. Then there exists a space W such that $Y \sim X \oplus W$ and we deduce

$$Y \sim X \oplus W \sim X \oplus X \oplus W \sim X \oplus Y.$$

Also there exists some space Z such that

$$X \sim Z \oplus Y \sim Z \oplus \left(\sum_{n \in \mathbb{N}} E_n \right).$$

This UFDD satisfies the hypotheses of Theorem 2.6 or Theorem 2.9. We deduce that for some $K \in \mathbb{N}$, $X \sim X \oplus \sum_{n \geq K} E_n$. As the decomposition is finite-dimensional and X is isomorphic to its hyperplanes, it follows that

$$X \sim X \oplus Y. \blacksquare$$

In [1], Casazza proved that if a Banach space X is an l_p -sum of finite-dimensional spaces and is primary, then $X \sim l_p(X)$, and thus X has the SBP. The following Corollary 2.12 extend this result to l_p -sums of finite-dimensional spaces which are not perfectly decomposable or not ergodic. We point out here that to prove Corollary 2.12, we need uniformity in the result of Proposition 2.11. This uniformity is one of the results we get which was not proved in the paper of Kalton.

Proposition 2.11. *Let X be a Banach space with a UFDD $X = \sum_{n=1}^{+\infty} E_n$. Assume this UFDD is not perfect or the relation E_0 is not Borel reducible to near isomorphism between subspaces of X of the form $X(\alpha) = \sum_{\alpha(n)=1} E_n$, $\alpha \in 2^\omega$ (for example X could be non nearly ergodic). Then there exists $N \in \mathbb{N}$ and an infinite sequence of disjoint subsets $(B_k)_{k \in \mathbb{N}}$ of $[N, +\infty)$ such that if $Y = \sum_{n=N}^{+\infty} E_n$, then $Y \sim \sum_{k \in \mathbb{N}} (\sum_{i \in B_k} E_i)$, with $\sum_{i \in B_k} E_i$ uniformly isomorphic to Y .*

Proof. By Proposition 2.4 or the proof of Theorem 2.9, we know that some \simeq -class is non-meager. We start as in the proof of Theorem 2.6, and using the same notation. Let α_0 be in some fixed non-meager \simeq -class, we may find K such that the set \mathcal{A} of α 's such that $X(\alpha) \sim^K X(\alpha_0)$ is non-meager, and thus comeager in some $N(u)$, $u \in 2^\omega$. We note that, by adding a finite sum of spaces E_i , and up to modifying the constant K and α_0 , we may assume that $u(i) = 1$ for all $i \leq |u|$ and also that $\alpha_0 \in N(u)$.

As a preliminary result, let us prove that the non-meager \simeq -class we get corresponds to the isomorphism class of X . We let $X(u) = \sum_{i \leq |u|} E_i$. Let $N = |u| + 1$. We apply the same proof as in Theorem 2.6 to get, for all $Y = \sum_{i \in I} E_i$, $I \subset [N, +\infty)$:

$$X(\alpha_0) \sim X(\alpha_0) \oplus Y.$$

In particular,

$$X(\alpha_0) \sim X(\alpha_0) \oplus \sum_{i \geq N} E_i,$$

and thus

$$X(u) \oplus X(\alpha_0) \sim X(\alpha_0) \oplus X.$$

On the other hand, we also have for all $Y = \sum_{i \in I} E_i$, $I \subset [N, +\infty)$:

$$X \sim X \oplus Y.$$

Choose Y such that $X(\alpha_0) = X(u) \oplus Y$, then

$$X \oplus X(u) \sim X \oplus X(\alpha_0).$$

Finally, we deduce that $X(u) \oplus X(\alpha_0) \sim X(u) \oplus X$, and as $X(u)$ is finite-dimensional, that $X(\alpha_0) \sim X$.

So, modifying K if necessary, we may assume that $\alpha_0(i) = 1, \forall i$, that is $X(\alpha_0) = X$. Now we prove the result about the decomposition. We note that the characterization of comeager subsets of 2^ω in terms of partitions of \mathbb{N} , that we used in Theorem 2.6, can be generalized to an infinite partition (see [6] about this). So from the fact that the set of α 's such that $X \sim^K X(\alpha)$ is comeager in $N(u)$, we get a sequence $(B_n)_{n \in \mathbb{N}}$ of disjoint subsets of $[N, +\infty)$ such that:

- (a) $X \sim^K X(u) \oplus \sum_{i \in B_k} E_i$, for all $k \in \mathbb{N}$, and
- (b) $X \sim X(u) \oplus \sum_{k \in \mathbb{N}} (\sum_{i \in B_k} E_i)$.

Let $Y = \sum_{n=N}^{+\infty} E_n$. From (b), we have that

$$X(u) \oplus Y = X \sim X(u) \oplus \sum_{k \in \mathbb{N}} (\sum_{i \in B_k} E_i),$$

and thus as $X(u)$ is finite-dimensional,

$$Y \sim \sum_{k \in \mathbb{N}} (\sum_{i \in B_k} E_i).$$

From (a), we get

$$X(u) \oplus Y = X \sim^K X(u) \oplus (\sum_{i \in B_k} E_i), \forall k \in \mathbb{N},$$

and so,

$$Y \sim (\sum_{i \in B_k} E_i), \forall k \in \mathbb{N},$$

where the constant of isomorphism depends only on K and on $\dim X(u)$. ■

Corollary 2.12. *Let $Z = c_0$ or l_p for $1 \leq p < +\infty$. Let $X = (\sum_{n \in \mathbb{N}} E_n)_Z$, where for each n , E_n is finite-dimensional. Assume this UFDD is not perfect or X is not ergodic. Then $X \sim (\sum X)_Z$. So by Pelczynski's Decomposition Method, X has the SBP.*

Proof. Let X be as in the hypotheses. First note that any l_p -sum, and in particular X or any subspace of X of the form $X(\alpha), \alpha \in 2^\omega$, contains a complemented copy of l_p and so, is isomorphic to its hyperplanes. In particular, two subspaces $X(\alpha)$ and $X(\beta)$, $\alpha, \beta \in 2^\omega$, are nearly isomorphic if and only if they are isomorphic, and so the relation E_0 is Borel reducible to near isomorphism between these subspaces if and only if it is Borel reducible to isomorphism between them. This implies that the hypotheses of Proposition 2.11 are satisfied.

So the conclusion of Proposition 2.11 holds, and we note that the copies are uniform and that the infinite direct sum is, in this case, an l_p -sum. So for some $N \in \mathbb{N}$, $Y = \sum_{n \geq N} E_n$ satisfies $Y \sim l_p(Y)$. As X is isomorphic to its hyperplanes, it follows that $X \sim Y$, and so $X \sim l_p(X)$. ■

3. A continuum of mutually non-isomorphic Banach spaces which are complemented in each other.

We now turn to the main theorem of this paper, which provides a family of cardinality the continuum of mutually non-isomorphic separable Banach spaces which are complemented in each other (Theorem 3.9). In order to present this family of Banach spaces, we need to fix some notation and background from [13].

3.1. Preliminaries.

Let c_{00} be the vector space of all complex sequences which are eventually 0. Let $(e_n)_{n \in \mathbb{N}}$ be the standard basis of c_{00} . Given a vector $a = \sum a_n e_n$ its *support*, denoted $\text{supp}(a)$, is the set of n such that $a_n \neq 0$. Given subsets E, F of \mathbb{N} , we say that $E < F$ if every element of E is less than every element of F . If $x, y \in c_{00}$, we say that $x < y$ if $\text{supp}(x) < \text{supp}(y)$. If $x_1 < x_2 < \dots < x_n$, then we say that the vectors x_1, x_2, \dots, x_n are *successive*. An infinite sequence of successive non-zero vectors is also called a *block basis* and a subspace generated by a block basis is a *block subspace*.

Given a subset E of \mathbb{N} and a vector a as above, we write Ea for the vector $\sum_{n \in E} a_n e_n$. An interval of integers is a set of the form $\{m, m+1, \dots, n\}$, where $m, n \in \mathbb{N}$. The *range* of a vector x , written $\text{ran}(x)$, is the smallest interval containing $\text{supp}(x)$.

The following set of functions was first defined by Schlumprecht in [19] except for condition (vi) which was added in [13]. \mathcal{F} denotes the set of functions $f : [1, \infty) \rightarrow [1, \infty)$ satisfying the following conditions.

- (i) $f(1) = 1$ and $f(x) < x$ for every $x > 1$;
- (ii) f is strictly increasing and tends to infinity;
- (iii) $\lim_{x \rightarrow \infty} x^{-q} f(x) = 0$ for every $q > 0$;
- (iv) the function $x/f(x)$ is concave and non-decreasing;
- (v) $f(xy) \leq f(x)f(y)$ for every $x, y \geq 1$;
- (vi) the right derivate of f at 1 is positive.

Let \mathcal{X} stand for the set of normed spaces $(c_{00}, \|\cdot\|)$ such that the sequence $(e_n)_{n \in \mathbb{N}}$ is a normalized bimonotone basis, this means that $\|Ex\| \leq \|x\|$ for every vector $x \in c_{00}$ and every interval E . Given $X \in \mathcal{X}$ and $f \in \mathcal{F}$, it is said that X satisfies a *lower f-estimate* if, given any vector $x \in X$ and any sequence of intervals $E_1 < E_2 < \dots < E_n$, we have $\|x\| \geq f(n)^{-1} \sum_{i=1}^n \|E_i x\|$.

Given two infinite subsets A and B of \mathbb{N} , Gowers and Maurey define the *spread from A to B* to be the map $S_{A,B} : c_{00} \rightarrow c_{00}$ defined as follows. Let ρ be the order-preserving bijection from A to B , then $S_{A,B}(e_n) = e_{\rho(n)}$ when $n \in \mathbb{N}$, and $S_{A,B}(e_n) = 0$ otherwise.

Given any set \mathcal{S} of spreads, they say that it is a *proper set* if it is closed under composition and taking adjoints and if for every $(i, j) \neq (k, l)$, there are only finitely many spreads $S \in \mathcal{S}$ for which $e_i^*(Se_j) \neq 0$ and $e_k^*(Se_l) \neq 0$.

For every Banach space X satisfying a lower f -estimate for some $f \in \mathcal{F}$, and for every subspace Y of X generated by a block basis, they define a seminorm $\|\cdot\|$ on the set $L(Y, X)$ of linear mappings from Y to X as follows. For $X \in \mathcal{X}$, and every integer $N \geq 1$, consider the equivalent norm on X defined by

$$\|x\|_{(N)} = \sup \sum_{i=1}^N \|E_i x\|,$$

where the supremum is extended to all sequences E_1, E_2, \dots, E_N of successive intervals. Let $\mathcal{L}(Y)$ be the set of sequences $(x_n)_{n \in \mathbb{N}}$ of successive vectors in Y such that $\|x_n\|_{(n)} \leq 1$, for every $n \in \mathbb{N}$. Now let

$$|||T||| = \sup_{x \in \mathcal{L}(Y)} \limsup_n \|T(x_n)\|.$$

Finally, we also recall that two Banach spaces X and Y are said to be totally incomparable if no infinite dimensional subspace of X is isomorphic to a subspace of Y .

3.2. The main result.

The principal purpose of this section is to prove Theorem 3.9. Before that, we need some auxiliary results which are similar to the ones involved in the construction by Gowers and Maurey of the Banach space X_1 isomorphic to its cube but not to its square. We shall improve these results in two directions. First we shall need to have a family of spaces X_r constructed on the model of X_1 , for $1/2 \leq r \leq 1$, and we shall take care that for $r \neq r'$, X_r and $X_{r'}$ are totally incomparable spaces. For this we shall have to write new versions of some technical lemmas in [13]. Then, we shall need to know that each X_r is not nearly isomorphic to its square (instead of just non-isomorphic). This requires a little bit of extra care in the proofs as well.

The proof of Lemma 3.1 is implicit in [13], page 864, and in the proof of [13], Lemma 9, in the case $f(x) = \log_2(x + 1)$.

Lemma 3.1. *Let $f \in \mathcal{F}$ and $J \subset \mathbb{N}$ be such that, if $m, n \in \mathbb{N}$, $m < n$, then $\log \log \log n \geq 4m^2$. Write J in increasing order as $\{j_1, j_2, \dots\}$ and let $K = \{j_1, j_3, j_5, \dots\}$. Suppose that*

- (a) $f^{1/2} \in \mathcal{F}$;
- (b) $f(j_1) > 256$;
- (c) $\exp \exp j_n < f^{-1}(f(j_m))^{1/2}$, $\forall m, n \in \mathbb{N}, m < n$;
- (d) $16f(x^{1/2}) \geq f(x)$, $\forall x \geq 0$;
- (e) $f(j_n)^{3/2} > f(j_n^3)$, $\forall n \in \mathbb{N}$;

(f) *For every $N \in J \setminus K$ and x_0 in the interval $[\log N, \exp N]$, the function given by the tangent to $(x \rightarrow x/f(x))$ at x_0 is at least $x/f^{1/2}(x)$ for all positive x outside the interval $[\log \log N, \exp \exp N]$.*

Then for every $K_0 \subset K$, there is a function $g \in \mathcal{F}$ such that $f \geq g \geq f^{1/2}$, $g(k) = f(k)^{1/2}$ whenever $k \in K_0$ and $g(x) = f(x)$ whenever $N \in J \setminus K_0$ and x in the interval $[\log N, \exp N]$.

The next lemmas extend some technical results of [13] concerning $f(x) = \log_2(x + 1)$ to the case of $f(x) = (\log_2(x + 1))^r$, $r \in [1/2, 1]$. Their calculus proofs are postponed until Section 5.

Lemma 3.2. *Let f_r be defined on $[1, +\infty)$ by $f_r(x) = (\log_2(x + 1))^r$ for every $r \in (0, 1]$. Then f_r belongs to the class \mathcal{F} .*

Lemma 3.3. *There exists $J \subset \mathbb{N}$ such that writing it in increasing order as $\{j_1, j_2, \dots\}$ and letting $K = \{j_1, j_3, j_5, \dots\}$, we have that for every $K_0 \subset K = (j_{2i-1})_{i \in \mathbb{N}}$ and every $r \in [1/2, 1]$, there is a function $g_r \in \mathcal{F}$ such that $f_r \geq g_r \geq f_r^{1/2}$, $g_r(k) = f_r(k)^{1/2}$ whenever $k \in K_0$ and $g_r(x) = f_r(x)$ whenever $N \in J \setminus K_0$ and x in the interval $[\log N, \exp N]$.*

The case $r = 1$ in the following theorem is the main result of [8], see [8, Theorem 5]. By using Lemma 3.3 instead of [6, Lemma 6] in the argumentation of [8] we obtain:

Theorem 3.4. *Let \mathcal{S} be a proper set of spreads and $r \in [1/2, 1]$. There exists a Banach space $X_r(\mathcal{S})$ satisfying a lower f_r -estimate with the following three properties.*

- (i) *For every $x \in X_r(\mathcal{S})$ and every $S_{A,B} \in \mathcal{S}$, $\|S_{A,B}x\| \leq \|x\|$ and therefore $\|S_{A,B}x\| = \|x\|$ if $\text{supp}(x) \subset A$.*
- (ii) *If Y is a subspace of $X_r(\mathcal{S})$ generated by a block basis, then every operator from Y to $X_r(\mathcal{S})$ is in the $\|\cdot\|$ -closure of the set of restrictions to Y of the operators in the algebra \mathcal{A} generated by \mathcal{S} . In particular, all operators on $X_r(\mathcal{S})$ are $\|\cdot\|$ -perturbations of operators in \mathcal{A} .*
- (iii) *The seminorm $\|\cdot\|$ satisfies the algebra inequality $\|UV\| \leq \|U\| \|V\|$.*

We are now in position to define our family of totally incomparable versions of the 'cube but not square' space X_1 of Gowers and Maurey. The definitions follow the ones in [13]. For $i = 0, 1, 2$ let A_i be the set of positive integers equal $i + 1 \pmod{3}$, let S'_i be the spread from \mathbb{N} to A_i and \mathcal{S}' be the semigroup generated by S'_0 , S'_1 and S'_2 and their adjoints. In [13], page 560, it was shown that \mathcal{S}' is a proper set. Given $r \in [1/2, 1]$, the Banach space we are interested in is the space $X_r(\mathcal{S}')$ obtained by Theorem 3.4. As in [13] it will be useful to define it slightly less directly as follows.

Let \mathcal{T} be the ternary tree $\cup_{n=0}^{\infty} \{0, 1, 2\}^n$. Let Y_{00} be the vector space of finitely supported scalar sequences indexed by \mathcal{T} (including the empty sequence). Denote the canonical basis of Y_{00} by $(e_t)_{t \in \mathcal{T}}$, write e for e_\emptyset . If $s, t \in \mathcal{T}$, let $s \wedge t$ stand for the concatenation of s and t . We shall now describe some operators on Y_{00} .

Let S_i for $i = 0, 1, 2$ be defined by their action on the basis as follows: $S_i e_t = e_{t \sim i}$. The adjoint S^* acts in the following way: $S_i^* e_t = e_s$ if t is of the form $t = s \sim i$ and $S_i^* e_t = 0$ otherwise.

If P denotes the natural rank one projection on the line $\mathbb{R}e$, then we denote by \mathcal{I} and \mathcal{A} respectively the proper set generated by S_0 , S_1 and S_2 , and the algebra generated by this proper set. Strictly speaking, \mathcal{I} is not a proper set, but it is easy to embed \mathcal{I} in \mathbb{N} so that the maps S_0 , S_1 and S_2 become spreads as defined earlier.

In order to obtain the space $X_r(\mathcal{S}')$, consider the subset \mathcal{T}' of \mathcal{T} consisting of all words $t \in \mathcal{T}$ that do not start with 0 (including the empty sequence). We modify the definition of S_0 slightly, by letting $S'_0 e$ equal e instead of e_0 . The operators S'_1 and S'_2 are defined exactly as S_1 and S_2 were.

To each $s = (i_1, \dots, i_n) \in \mathcal{T}'$ we can associate the integer $n_s = 3^{n-1}i_1 + \dots + 3i_{n-1} + i_n + 1$, with $n_\emptyset = 1$, and this defines a bijection between \mathcal{T}' and \mathbb{N} . The operators S'_0 , S'_1 and S'_2 coincide with the spreads on c_{00} defined earlier, so we can define \mathcal{S}' to be the proper set they generate and obtain the space $X_r(\mathcal{S}')$.

Let Y be the completion of Y_{00} equipped with the l_1 norm, in other words let $Y = l_1(\mathcal{T})$ and let \mathcal{E} denote the norm closure of \mathcal{A} in $L(Y)$. Let also \mathcal{J} the closed two-sided ideal in \mathcal{E} generated by P . Let \mathcal{O} denote the quotient algebra \mathcal{E}/\mathcal{J} .

Now we consider the algebra \mathcal{A}' generated by \mathcal{S}' . In [13], Lemma 20, it was proved that $\|\cdot\|$ is a norm on \mathcal{A}' . If we write \mathcal{G} for the $\|\cdot\|$ -completion of \mathcal{A}' then Theorem 3.4 implies that \mathcal{G} is a Banach algebra and there exists a unital algebra homomorphism ϕ from $L(X_r(\mathcal{S}'))$ to \mathcal{G} ([13], page 550).

In [13], Lemma 25, it was shown that there is a norm-one algebra homomorphism θ from \mathcal{G} to \mathcal{O} .

Finally, let V be an arbitrary set and $\psi : V \rightarrow V$ a function, we denote by ψ_3 the function from the set of matrices $M_3(V)$ to $M_3(V)$ given by $\psi_3((v_{i,j})_{1 \leq i,j \leq 3}) = (\psi(v_{i,j}))_{1 \leq i,j \leq 3}$, for every $(v_{i,j})_{1 \leq i,j \leq 3} \in M_3(V)$.

Remark 3.5. Gowers and Maurey proved that $X_1(\mathcal{S}')$ is isomorphic to its cube $X_1(\mathcal{S}')^3$ ([13], page 563). Likewise $X_r(\mathcal{S}')$ is isomorphic to its cube $X_r(\mathcal{S}')^3$. Furthermore, it is important to note that the norms of the projections involved in $X_r(\mathcal{S}') \xrightarrow{c} X_r(\mathcal{S}')^2$ and $X_r(\mathcal{S}')^2 \xrightarrow{c} X_r(\mathcal{S}')$ do not depend on the number $r \in [1/2, 1]$. Indeed, letting

$$X_j = \left\{ \sum_{i=1}^{\infty} x_{3i+j} e_{3i+j} \in X_r(\mathcal{S}') \right\}$$

for every $j = 0, 1, 2$, we have by Theorem 3.4 (i)

- (a) X_j is isometric to $X_r(\mathcal{S}')$ for every $j = 0, 1, 2$.
- (b) $X_r(\mathcal{S}') = X_0 \oplus X_1 \oplus X_2$.
- (c) The operator P_r from $X_r(\mathcal{S}')$ onto $X_0 \oplus X_1$ defined by $P_r(x) = S_{\mathbb{N}, A_0}(x) + S_{\mathbb{N}, A_1}(x)$ is a projection with $\|P_r\| \leq 2$.

(d) The operator Q_r from $X_0 \oplus X_1$ onto X_0 defined by $Q_r = S_{\mathbb{N}, A_0}(x)$ is a projection with $\|Q_r\| = 1$.

Lemma 3.6. $X_r(\mathcal{S}')$ is nearly isomorphic to $X_r(\mathcal{S}')^2$ for no $r \in [1/2, 1]$.

Proof. It is inspired by [13], Theorem 26, where it was proved that $X_1(\mathcal{S}')$ is not isomorphic to its square $X_1(\mathcal{S}')^2$. Given $r \in [1/2, 1]$, denote $X_r(\mathcal{S}')$ by X and assume that some finite codimensional subspace of X is isomorphic to a finite codimensional subspace of X^2 . We consider the two possible cases.

First case: $X \sim X^2 \oplus F$, for some finite-dimensional space F . Let U be an isomorphism from X onto $X^2 \oplus F$, and assume without loss of generality that $F \subset X$. Write $U = (U_1, U_2, U_3)$, where $U_1 \in L(X)$, $U_2 \in L(X)$ and $U_3 \in L(X, F)$.

Let H be such that $X = F \oplus H$. Thus there exists an isomorphism V from X^2 onto H . Defining $V_1(z) = V(x, 0)$ and $V_2(x) = V(0, x)$, for every $x \in X$, we have that $V_1 \in L(X)$, $V_2 \in L(X)$ and $V(x_1, x_2) = V_1(x_1) + V_2(x_2)$, for every $(x_1, x_2) \in X^2$.

Next consider the isomorphism $\Psi : X \oplus X^2 \rightarrow X^2 \oplus F \oplus H$ defined by

$$\Psi(x_1, (x_2, x_3)) = U(x_1) + V(x_2, x_3)$$

Its matrix as linear map from X^3 to X^3 is given by

$$A = \begin{pmatrix} U_1 & 0 & 0 \\ U_2 & 0 & 0 \\ U_3 & V_1 & V_2 \end{pmatrix}$$

where U_3 is seen as an operator from X into X . Since A is an invertible element of $M_3(L(X))$, it follows that $\theta_3\Phi_3(A)$ is invertible in $M_3(\mathcal{O})$. Therefore, by [13], Corollary 24, there exists an invertible element B in $M_3(\mathcal{E})$ such that $\Pi_3(B) = \theta_3\Phi_3(A)$, where Π is the canonical application from \mathcal{O} onto \mathcal{E}/\mathcal{J} .

As was noted in [13], page 550, the Kernel of ϕ is the set of $T \in L(X)$ satisfying $\|T\| = 0$. The basis $(e_n)_{n \in \mathbb{N}}$ being shrinking ([13], page 551), the Kernel of ϕ contains the compact operators. Indeed for any $x = (x_n)_{n \in \mathbb{N}} \in \mathcal{L}(Y)$, the sequence $(x_n)_{n \in \mathbb{N}}$ is bounded and converges weakly to 0. So if T is compact, $(T(x_n))_{n \in \mathbb{N}}$ converges in norm to 0. In particular, $\phi(U_3) = 0$, because U_3 is of finite rank.

On the other hand, according to [13], page 564, \mathcal{J} consists exactly of the compact w^* -continuous operators on l_1 . Hence

$$B = \begin{pmatrix} u & c_1 \\ c_2 & v \end{pmatrix}$$

where $u \in M_{2,1}(\mathcal{E})$, $v \in M_{1,2}(\mathcal{E})$, $c_1 \in M_{1,1}(\mathcal{E})$ and $c_2 \in M_{2,2}(\mathcal{E})$, with c_1 and c_2 compacts. It follows from [17], page 80, that the operator D below defined is Fredholm

$$D = \begin{pmatrix} u & 0 \\ 0 & v \end{pmatrix}$$

Consequently u and v are also Fredholm operators; which is absurd because there exists no Fredholm element in $M_{2,1}(\mathcal{E})$ ([13], Lemma 21).

Second case: $X^2 \sim X \oplus F$ for some finite-dimensional space F .

In this case, we would have $X^3 \sim X^2 \oplus F$. According to Remark 3.5, $X \sim X^3$. Thus by the first case we also would obtain a contradiction. ■

We recall the definition of *Rapidly Increasing Sequences* given in [13]. For $X \in \mathcal{X}$, $x \in X$ and every integer $N \geq 1$, recall that

$$\|x\|_{(N)} = \sup \sum_{i=1}^N \|E_i x\|,$$

where the supremum is extended to all sequences E_1, E_2, \dots, E_N of successive intervals.

For $0 < \epsilon \leq 1$ and $f \in \mathcal{F}$, we say that a sequence x_1, x_2, \dots, x_N of successive vectors *satisfies the RIS(ϵ) condition for the function f* if there is a sequence $(2N/f'(1))f^{-1}(N^2/\epsilon^2) < n_1 < \dots < n_N$ of integers (where $f'(1)$ is the right derivate in 1) such that $\|x_i\|_{(n_i)} \leq 1$ for each $i = 1, \dots, N$ and

$$\epsilon f(n_i)^{1/2} > |\text{ran}(\sum_{j=1}^{i-1} x_j)|$$

for every $i = 2, \dots, N$ ([13], page 546).

Lemma 3.7. *Let \mathcal{S}_1 and \mathcal{S}_2 be proper sets of spreads and $r, s \in [1/2, 1]$, with $r \neq s$. Then the Banach spaces $X_r(\mathcal{S}_1)$ and $X_s(\mathcal{S}_2)$ are totally incomparable.*

Proof. Fix $r > s$ in $[1/2, 1]$ and suppose that $X_r(\mathcal{S}_1)$ and $X_s(\mathcal{S}_2)$ are not totally incomparable. Thus, by a standard perturbation argument, we may find an infinite sequence of successive non-zero vectors $(z_n)_{n \in \mathbb{N}}$ in $X_r(\mathcal{S}_1)$, and an isomorphism T from $\overline{\text{span}}\{z_n : n \in \mathbb{N}\}$ into $X_s(\mathcal{S}_2)$, such that $(T(z_n))_{n \in \mathbb{N}}$ is successive in $X_s(\mathcal{S}_2)$.

For N in $K \subset J$, we may then block $(z_n)_{n \in \mathbb{N}}$ to construct a sequence x_1, x_2, \dots, x_N satisfying the R.I.S(1) condition for the function f_r with $\|x_i\| \geq 1/2$ ([13], Lemma 4). Now putting $x = \sum_{n=1}^N x_n$ we obtain by the lemma analogous to Lemma 7 in [13] that

$$\|x\| \leq \frac{4N}{f_r(N)}.$$

Consequently

$$\|T(x)\| \leq \|T\| \frac{4N}{f_r(N)}.$$

On the other hand, since $T(x_n)$ is successive in $X_s(\mathcal{S}_2)$ and $X_s(\mathcal{S}_2)$ satisfies a lower f_s -estimate we deduce that

$$\|T(x)\| \geq \frac{1}{f_s(N)} \sum_{n=1}^N \|T(x_n)\| \geq \frac{1}{f_s(N)} \frac{1}{\|T^{-1}\|} \sum_{n=1}^N \|x_n\| \geq \frac{N}{2} \frac{1}{f_s(N)} \frac{1}{\|T^{-1}\|}.$$

It follows that

$$(\log_2(N+1))^{r-s} \leq 8 \|T\| \|T^{-1}\|,$$

which is a contradiction for N large enough. ■

The last ingredient for our proof is the following standard lemma from [14].

Lemma 3.8. *Let $(Y_i)_{i \in \mathbb{N}}$ be a sequence of Banach spaces. Suppose that the Banach space X is isomorphic to a subspace of $l_2(Y_i)_{i \in \mathbb{N}}$. Then some subspace of X is isomorphic to a subspace of Y_n for some $n \in \mathbb{N}$ or l_2 is isomorphic to a subspace of X .*

We are now ready to prove our main result.

Theorem 3.9. *There exists a family of separable Banach spaces $(X_\alpha)_{\alpha \in \{1,2\}^\omega}$ such that*

- (a) $X_\alpha \xrightarrow{c} X_\beta$ for every α and β in $\{1,2\}^\omega$.
- (b) $X_\alpha \not\sim X_\beta$ for every $\alpha \neq \beta$.

Proof. Let \mathcal{S}' be the spread considered after Theorem 3.4. We pick a sequence $(r_n)_{n \in \mathbb{N}}$ of numbers in $[1/2, 1]$, with $r_m \neq r_n$ whenever $m \neq n$ and define $Z_n = X_{r_n}(\mathcal{S}')$, for every $n \in \mathbb{N}$.

We then define for $\alpha \in \{1,2\}^\omega$, the following l_2 -sum of Banach spaces:

$$X_\alpha = (\sum_{n=1}^{\infty} Z_n^{\alpha(n)})_2.$$

It follows from Remark 3.5 that any two such spaces are complemented in each other. We next assume that there exists an isomorphism T from X_β onto X_α and intend to prove that $\alpha = \beta$. Let P_1 be the canonical projection from X_α onto $Z_1^{\alpha(1)}$, and Q_1 be the canonical projection from X_α onto $(\sum_{n=2}^{\infty} Z_n^{\alpha(n)})_2$. We define analogously P'_1 and Q'_1 to be the projections corresponding to the space X_β .

We now claim that $S = Q_1 T|_{Z_1^{\beta(1)}}$ is strictly singular, that is, S cannot be an isomorphism on any infinite dimensional subspace of $Z_1^{\beta(1)}$.

Indeed, otherwise, there exists an infinite dimensional subspace Z of $Z_1^{\beta(1)}$, such that $Q_1 T|_Z$ is an isomorphism into, so Z is isomorphic to some subspace of $(\sum_{n=2}^{\infty} Z_n^{\alpha(n)})_2$. Since $Z_1^{\beta(1)}$ has no unconditional basic sequence ([13], page 567), it contains no subspace isomorphic to l_2 and therefore by Lemma 3.8, we deduce that Z contains an infinite dimensional subspace which is isomorphic to a subspace of $Z_n^{\alpha(n)}$ for some $n \geq 2$, contradicting Lemma 3.7.

We then define the operators $U : Z_1^{\beta(1)} \rightarrow Z_1^{\alpha(1)}$ and $V : Z_1^{\alpha(1)} \rightarrow Z_1^{\beta(1)}$ by

$$U(x) = P_1 T(x) \quad \text{and} \quad V(x) = P'_1 T^{-1}(x).$$

We consider $VU \in L(Z_1^{\beta(1)})$. For any $x \in Z_1^{\beta(1)}$, we deduce that

$$VU(x) = VP_1 T(x) = V(Id_{X_\alpha} - Q_1)T(x) = V(T(x) - Q_1 T(x)) = VT(x) - VS(x),$$

therefore

$$VU(x) = P'_1(x) - VS(x) = x - VS(x),$$

that is, $VU = Id_{Z_1^{\beta(1)}} + s$, where s is strictly singular.

Now by symmetry, we also have that $UV = Id_{Z_1^{\alpha(1)}} + s'$, where s' is strictly singular. Then UV and VU are Fredholm operators ([17], page 80). It follows that U and V are isomorphisms on finite codimensional subspaces and have finite dimensional cokernels, hence are Fredholm. Consequently $Z_1^{\alpha(1)}$ and $Z_1^{\beta(1)}$ have isomorphic finite codimensional subspaces, and by Lemma 3.6, this means that $\alpha(1) = \beta(1)$. This proof can be repeated for an arbitrary $n \in \mathbb{N}$, so we conclude that $\alpha = \beta$. ■

4. Some remarks and problems.

Problem 4.1. As already said, it comes easily from the properties of the space $X_1(\mathcal{S}_p)$ of Gowers and Maurey mentioned in the introduction that it satisfies $SBI(X_1(\mathcal{S}_p)) = p$. Does there exist a Banach space X with $SBI(X) = \aleph_0$? In particular, is the space X_E defined in [9] such a space?

Problem 4.2. $SBI(X) = 2^{\aleph_0}$ is the highest possible value for a separable Banach space X . The next step concerning separable Banach spaces should rather be expressed in terms of complexity of the relation of isomorphism. We refer to [5] or [18] for a survey about the notion of relative complexity of analytic equivalence relations on Polish spaces, applied to isomorphism between separable Banach spaces. How complex can be an equivalence relation R on 2^ω , which is Borel reducible to isomorphism between separable Banach spaces, with the condition that the image of the reducing map is formed by Banach spaces which are all complemented in each other?

As a consequence of Lemma 3.7, we also derive the following proposition. We recall that a property P of a Banach space is said to be a *three-space property* if whenever a Banach space X has a subspace Y which satisfies P and such that X/Y satisfies P , it follows that X satisfies P . See [3] for a survey on three-space problems.

Proposition 4.3. *Failing the Schroeder-Bernstein Property is not a three-space property.*

Proof. Let S be the right shift on c_{00} , that is, $S : c_{00} \rightarrow c_{00}$ is given by $S(a_1, a_2, \dots) = (0, a_1, a_2, \dots)$. Denote by \mathcal{S}_2 and \mathcal{S}_3 the proper set generated by S^2 and S^3 respectively. Consider the Banach spaces $X = X_1(\mathcal{S}_2)$ and $Y = X_{1/2}(\mathcal{S}_3)$ given by Theorem 3.4. By Lemma 3.7, X and Y are totally incomparable spaces.

We know by Theorem 19 in [12] and the remarks after this theorem that:

- (a) X is isomorphic to its subspaces of codimensions two but not to its hyperplanes.

- (b) Two finite-codimensional subspaces of Y are isomorphic if and only if their codimensions are equal mod 3.
- (c) Every complemented subspace of X (resp. Y) has finite dimension or codimension in X (resp. Y).

Clearly from (a) and (b) X and Y do not have the SBP. In fact $SBI(X) = 2$ and $SBI(Y) = 3$. So, to prove the Proposition it suffices to show that $X \oplus Y$ has the SBP.

Suppose then that $Z \xrightarrow{c} X \oplus Y$ and $X \oplus Y \xrightarrow{c} Z$ for some Banach space Z . Since X and Y are totally incomparable spaces, by Theorem 23 in [20], we have that $Z = Z_1 \oplus Z_2$, where $Z_1 \xrightarrow{c} X$ and $Z_2 \xrightarrow{c} Y$. Moreover, $X \xrightarrow{c} Z_1 \oplus Z_2$ and X and Z_2 are totally incomparable spaces. Consequently, again by Theorem 23 in [20], we conclude that Z_1 is an infinite dimensional space. According to (c) we deduce that $Z_1 \sim X$ or $Z_1 \sim X \oplus \mathbb{R}$. In the same way, we obtain that $Z_2 \sim Y$, $Z_2 \sim Y \oplus \mathbb{R}$ or $Z_2 \sim Y \oplus \mathbb{R}^2$.

Therefore Z is isomorphic to one of the following spaces: $X \oplus Y$, $X \oplus Y \oplus \mathbb{R}$, $X \oplus Y \oplus \mathbb{R}^2$ or $X \oplus Y \oplus \mathbb{R}^3$. Hence, to see that Z is isomorphic to $X \oplus Y$, it is enough to show that $X \oplus Y$ is isomorphic to its hyperplanes. But this is true because of (a) and (b). Indeed,

$$X \oplus Y \oplus \mathbb{R} \sim (X \oplus \mathbb{R}^2) \oplus Y \oplus \mathbb{R} \sim X \oplus (Y \oplus \mathbb{R}^3) \sim X \oplus Y. \blacksquare$$

Proposition 4.3 leads naturally to the following problems:

Problem 4.4. Assume X is a Banach space such that X^2 has the SBP. Does it follow that X has the SBP?

Problem 4.5. Is the SBP a three-space property?

A partial answer to Problem 4.5 was given by Casazza in [2]. He noticed that if X and Y have the SBP, and are totally incomparable spaces, then $X \oplus Y$ has the SBP.

As another immediate consequence of Theorem 3.4 and Lemma 3.7, we obtain the following result of I. Gasparis [10]. We recall that a Banach space X is hereditarily indecomposable if no closed subspace Y of X contains a pair of infinite dimensional closed subspaces M and N such that $Y = M \oplus N$.

Corollary 4.6. (I. Gasparis) *There exists a family of cardinality the continuum of separable totally incomparable hereditarily indecomposable Banach spaces.*

Proof. Let $\mathcal{S} = Id$ be the identity of c_{00} . Then, by [13], section 4.1, and using Lemma 3.7 we see that the spaces $(X_r(Id))_{r \in [1/2, 1]}$ given by Theorem 3.4 are a continuum of totally incomparable hereditarily indecomposable Banach spaces. ■

Remark 4.7. Gasparis gets in fact a stronger result, that is, a continuum of asymptotically l_1 hereditarily indecomposable Banach spaces. There is an

even simpler way to obtain the result of Gasparis, if one doesn't care for the asymptotically l_1 part. In [4] it was constructed a family $X_p, 1 < p < +\infty$ of (uniformly convex) hereditarily indecomposable Banach spaces with a Schauder basis. Each X_p satisfies the following norm inequality for successive vectors x_1, \dots, x_n on the basis:

$$\frac{1}{f(n)^{1/2}} \left(\sum_{k=1}^n \|x_k\|^p \right)^{\frac{1}{p}} \leq \left\| \sum_{k=1}^n x_k \right\| \leq \left(\sum_{k=1}^n \|x_k\|^p \right)^{\frac{1}{p}},$$

where as before, f is defined by $f(x) = \log_2(x+1)$. By the same argument as in Lemma 3.7, it follows from this inequality that for $p \neq p'$, X_p and $X_{p'}$ are totally incomparable spaces.

5. Appendix.

In this appendix, we give the proofs of Lemmas 3.2 and 3.3 which were postponed in Section 3.

Proof of Lemma 3.2. Since $f(x) = \log_2(x+1)$ is in \mathcal{F} , it follows that (i), (ii), (iii), (v) and (vi) of the definition of \mathcal{F} hold also for $f_r(x) = f^r(x)$. To show that f_r belongs to \mathcal{F} , it only remains to show that the second derivate of the function $F(x) = x/f_r(x)$ is negative on $[1, \infty)$. We have,

$$F''(x) = \frac{r(\log_2(x+1))^r \log_2 e}{(x+1)^2 (\log_2(x+1))^{2(r+1)}} (-x \log_2(x+1) - 2 \log_2(x+1) + (r+1)x \log_2 e).$$

Consider $D(x) = -x \log_2(x+1) - 2 \log_2(x+1) + (r+1)x \log_2 e$. Then $D(1) < 0$, because $r \leq 1$ and $e^2 < 8$. Thus it is enough to prove that $D'(x) < 0$ for all $x \geq 1$. Compute

$$D'(x) = \frac{1}{x+1} (-x \log_2(x+1) - x \log_2 e - 2 \log_2 e + (r+1)(x+1) \log_2 e).$$

$$\text{Let } H(x) = -x \log_2(x+1) - x \log_2 e - 2 \log_2 e + (r+1)(x+1) \log_2 e.$$

In particular, $H(1) = -2 + (2r-1)\log_2 e < 0$ since $r \leq 1$. Also, $H'(x) = -\log_2(x+1) + (r-1)\log_2 e < 0$, $\forall x \geq 1$, because $r \leq 1$. Therefore $H(x) < 0$ for all $x \geq 1$. ■

To make clear the proof of Lemma 3.3, we stand out some simple inequalities.

- (1) $16 \log_2(x^{1/2} + 1) > \log_2(x+1)$, $\forall x \geq 1$.
- (2) $(\log_2(x+1))^{3/2} > \log_2(x^3 + 1)$, $\forall x \geq 1048576$.
- (3) $\log_2(x+1) \leq x^{1/4}$, $\forall x \geq 32^4$.
- (4) $x^{1/4} \leq (x/2)^{1/2}$, $\forall x \geq 32^4$.
- (5) $64x^3 < e^{x/2}$, $\forall x \geq 18$.
- (6) $x+1 < e^{x/2}$, $\forall x \geq 6$.

Proof of Lemma 3.3. Let $J = (j_n)_{n \in \mathbb{N}}$ be a subset of \mathbb{N} such that

$$j_1 > 10^{10^{10^{400}}} \text{ and } j_{n+1} > 10^{10^{10^{4(j_n)^2}}}, \forall n \in \mathbb{N}.$$

It suffices to verify that the hypothesis of Lemma 3.1 are satisfied for this J and for every f_r , with $r \in [1/2, 1]$.

Fix $r \in [1/2, 1]$. By Lemma 3.2 $f_r \in \mathcal{F}$ and clearly $\log \log \log n \geq 4m^2$, $\forall m, n \in J$, $m < n$.

(a) Since $f_r^{1/2} = f_{r/2}$, Lemma 3.2 implies that $f_r^{1/2} \in \mathcal{F}$.

(b) $f_r(j_1) > 256$ if and only if $j_1 > 2^{256^{1/r}} - 1$. Since $r \geq 1/2$ this is clearly true.

(c) $\exp \exp j_n < f_r^{-1}(f_r(j_m))^{1/2}$ if and only if $\log_2(1+e^{j_n}) < (\log_2(1+j_m))^{1/2}$.

But this last inequality follows from the definition of J .

(d) $16f_r(x^{1/2}) > f_r(x)$ if and only if $16^{1/r}\log_2(x^{1/2} + 1) > \log_2(x + 1)$. Since $r \leq 1$, this follows from (1).

(e) $f_r(p)^{3/2} > f_r(p^3)$ if and only if $(\log_2(p + 1))^{3/2} > \log_2(p^3 + 1)$. This is a consequence of (2).

(f) Fix $N \in J \setminus K$ and x_0 in the interval $[\log N, \exp N]$. The equation of the tangent $t(x)$ to $x/f_r(x)$ at x_0 is

$$t(x) = \frac{x_0}{f_r(x_0)} + \frac{1}{f_r(x_0)}\left(1 - \frac{rx_0}{(x_0 + 1)\log(x_0 + 1)}\right)(x - x_0).$$

Claim 1.

$$(7) \quad \frac{x_0}{2(\log_2(x_0 + 1))^{r+1}} \leq t(x), \quad \forall x \geq 0.$$

Indeed, since $t(0) = (rx_0^2 \log_2 e)/(x_0 + 1)(\ln(x_0 + 1))^{r+1}$ and $2 \leq e^{\frac{2rx_0}{x_0+1}}$, because $j_n \leq x_0$, $\log 2 \leq j_n/(j_n + 1)$, for every $n \in \mathbb{N}$ and $r \geq 1/2$, we deduce that

$$(8) \quad \frac{x_0}{2(\log_2(x_0 + 1))^{r+1}} \leq t(0).$$

Moreover, $r \leq 1$ implies that the angular coefficient of $t(x)$ is positive, hence $t(0) \leq t(x)$, $\forall x \geq 0$. So by (7) we conclude (8).

Claim 2: If $x < \log \log N$, then

$$(9) \quad \frac{x}{f_r(x)^{1/2}} \leq \frac{x_0}{2(\log_2(x_0 + 1))^{r+1}}.$$

Indeed, let $c = x_0/2(\log_2(x_0 + 1))^{r+1}$. Consequently (9) holds if and only if $x^{2/r} \leq c^{2/r} \log_2(x + 1)$.

Let $d(x) = c^{2/r} \log_2(x + 1) - x^{2/r}$.

$d(1) \geq 0$ if and only if $\log_2(x_0 + 1) \leq (x_0/2)^{1/(r+1)}$. Since $r \leq 1$, the last inequality is true because of (3) and (4).

Furthermore $d'(x) > 0$ if and only if $x^{(2-r)/r}(x + 1)^{2/r} < c^{2/r} \log_2 e$, that is

$$(10) \quad x^{(2-r)/r}(x + 1) \frac{2}{r} < \left(\frac{x_0^{1/2(r+1)}}{\log_2(x_0 + 1)}\right)^{4/r} x_0^{2/(r+1)} (\log_2(x_0 + 1))^{2(1-r)/r} \frac{\log_2 e}{2^{2/r}}.$$

Since $1/2 \leq r \leq 1$, it follows that $(2 - r)/r \leq 3$ and $2/r \leq 4$. So, the first side of (10) is less than or equal to $4x^3(x + 1)$. On the other hand, again

since $1/2 \leq r \leq 1$, we know that $1 \leq 4/r$, $1 \leq 2/(r+1)$, $0 \leq 2(1-r)/r$ and $16 \leq 1/2^{2/r}$. Moreover, by (7), $1 \leq x_0^{1/2(r+1)}/\log_2(x_0 + 1)$. Hence the second side of (10) is greater than or equal to $x_0/16$.

Therefore to prove (10) it suffices to show that $64(x+1)x^3 < x_0$.

To see this, suppose that $x < 18$, thus

$$64(x+1)x^3 \leq (\ln N)^{1/2} (\ln N)^{1/2} < x_0.$$

Now assume that $x \geq 18$. Hence by (5) and (6) we have

$$64(x+1)x^3 \leq e^{x/2}e^{x/2} < x_0.$$

Claim 3: If $\exp \exp N \leq x$, then $x \geq 2x_0$.

Indeed $2x_0 \leq 2 \exp N \leq \exp \exp N \leq x$.

Claim 4: For every $x \geq 2x_0$, we have

$$\frac{x}{4f_r(x_0)} \leq t(x).$$

Indeed, consider $d(x) = t(x) - x/4f_r(x_0)$. Thus $d(2x_0) > 0$ because $rx_0/(x_0 + 1) < 3/2 \log(x_0 + 1)$ and $d'(x) > 0$ because $rx_0/(x_0 + 1) < 3/4 \log(x_0 + 1)$.

Claim 5: If $\log \log N \leq x$, then

$$(11) \quad \frac{x}{f_r(x)^{1/2}} \leq \frac{x}{4f_r(x_0)}.$$

Indeed, (11) holds if and only if

$$16(\log_2(x_0 + 1))^2 \leq \log_2(x + 1).$$

But this is true by the definition of J , because

$$16(\log_2(x_0 + 1))^2 \leq 16(\log_2(e^N + 1))^2 \leq \log_2(e^{e^N} + 1) \leq \log_2(x + 1).$$

Finally, by Claims (1), (2), (3), (4) and (5) we deduce that $x/f_r(x)^{1/2} \leq t(x)$, for every x outside the interval $[\log \log N, \exp \exp N]$. ■

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